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Research, part of a Special Feature on New Methods for Adaptive Water Management

Dealing with Uncertainty in Flood Management Through Diversification

Jeroen C. J. H. Aerts, *Wouter Botzen*, *Anne van der Veen*, *Joerg Krywkow*, *and Saskia Werners*

ABSTRACT. This paper shows, through a numerical example, how to develop portfolios of flood management activities that generate the highest return under an acceptable risk for an area in the central part of the Netherlands. The paper shows a method based on Modern Portfolio Theory (MPT) that contributes to developing flood management strategies. MPT aims at finding sets of investments that diversify risks thereby reducing the overall risk of the total portfolio of investments. This paper shows that through systematically combining four different flood protection measures in portfolios containing three or four measures; risk is reduced compared with portfolios that only contain one or two measures. Adding partly uncorrelated measures to the portfolio diversifies risk. We demonstrate how MPT encourages a systematic discussion of the relationship between the return and risk of individual flood mitigation activities and the return and risk of complete portfolios. It is also shown how important it is to understand the correlation of the returns of various flood management activities. The MPT approach, therefore, fits well with the notion of adaptive water management, which perceives the future as inherently uncertain. Through applying MPT on flood protection strategies current vulnerability will be reduced by diversifying risk.

Key Words: *adaptive water management; diversification; flood risk; Modern Portfolio Theory; uncertainty; vulnerability.*

INTRODUCTION

Flood management in the Netherlands still relies strongly on technical engineering capacity. This is a historically generated situation in which water managers have developed highly qualified flood protection systems with the highest safety standards in the world (Vellinga 2003). The major storm surge of 1953, which flooded large coastal areas in the southwest of the Netherlands, initiated a boost in technical innovations in flood protection measures (Aerts and Droogers 2004). However, since the near floods in 1993 and 1995, flood management practices have been exploring new approaches other than only technical investments such as dikes or pumping stations. Furthermore, long-term developments such as economic growth and climate change pose a challenge to Dutch water management (IPCC 2001). Long-term trends are inherently uncertain and hence difficult to predict, which makes it difficult to translate these trends into particular investment demands for daily operational water management (DWW 2005*a*).

New approaches for dealing with future uncertainties in water management have been recently introduced (Gleick 2003). For example, the development of flood insurance, flood risk mapping systems, and general risk management approaches that specifically address the probability of certain future trends are commonly used in spatial planning research and are gaining increasing attention in water management (e.g., Burby et al. 1999). Furthermore, in the social sciences the concept of adaptive (water-) management has been introduced, which aims at more institutional flexibility and provides stakeholders with a central role in an iterative "social learning process" (Folke et al. 2002, Pahl Wostl et al. 2005, Downing et al. 2005). Also in climate and vulnerability sciences, it appears that the process of determining future vulnerability holds too many uncertainties and some authors advocate that research should focus on reducing current vulnerability instead of simulating vulnerability under long term climate change (e.g., Smit et al. 2000, Adger et al. 2004, O'Brien et al. 2004, Füssel and Klein 2006).

Furthermore, despite new developments in cost benefit analyses under uncertainty (e.g., Boardman et al. 2006), dealing with uncertainty in operational flood management remains a challenge. Some of these studies show how long run cost-benefit analysis can be done through the choice and use of statistically derived paths of the discount rate (Pearce et al. 2003, Groom et al. 2005). In most flood management studies, however, the selection of flood management investments relies very much on classical cost-benefit analysis or optimization approaches that have their origin in operations research (e.g., Levy and Hall 2005, Penning-Rowsell et al. 2005). The term risk in these studies represents the product of probability of a hydraulic event, e.g., “discharge peak,” of a given magnitude and the damage costs, i.e., consequences associated with such an event. This is an accepted rubric for flood risk management, which means that interventions in flood risk management involve one of two things: changing the probability-event relationship and changing the discharge-damage relationship. These two issues can be linked to costs, i.e., interventions, and benefits, i.e., avoidance of losses.

In the area of financial investments, however, the term risk is used differently. In an approach formulated as the Modern Portfolio Theory (MPT, Markovitz 1952), risk is referred to as the standard deviation of the return of an investment. MPT aims at finding sets of investments that diversify risks thereby reducing the overall risk of the total portfolio of investments. The terminology of MPT is adopted in our paper and risk is from here referred to as the standard deviation or variance of either the return of a particular investment or the standard deviation or variance of the return of a portfolio of investments.

Since in most current flood management studies the evaluation is primarily concerned with the costs and benefits of investments, it is worthwhile investigating what role the risk of such investments could play in these studies and whether or not the risk-return ratio provided useful additional information to the basic assumptions made in cost and benefit analysis for flood management investments. There are a number of studies that use the portfolio concept (e.g., Costanza et al. 2000, O'Brien and Sculpher 2000, Figge 2004, Fraser et al. 2005), but to our knowledge, there has been no application in flood management. Hence, in this paper we pursue an analogy with financial services where portfolio managers are not primarily concerned with the valuation of assets but rather about which securities to invest in and in what quantity (Tonhasca and Byrne 1994, Figge 2004, Fraser et al. 2005). The task of a water manager, by analogy, would be to construct a portfolio of flood management activities that generates the highest return under an acceptable risk. Moreover, a water management portfolio should be developed in such a way that the risk-return ratio will be optimized through diversification of activities in the portfolio, hence through choosing activities in the portfolio that are at least partly uncorrelated.

Since dealing with uncertainty is one of the key issues in adaptive water management, we explore in this paper how MPT can contribute to operationalize the concept of adaptive water management for developing flood management strategies in the Netherlands. We provide a numerical example that applies MPT in flood protection and discuss the advantages and drawbacks of MPT as compared to existing approaches. The objectives of the paper are to: (1) Discuss the concept of diversification as formulated in MPT (Section 2); (2) Apply a numerical example of MPT to a case study in the Netherlands (Section 3); and (3) Discuss the advantages and drawbacks of MPT in flood protection management (Section 4)

MODERN PORTFOLIO THEORY

The benefits of diversifying investments are widely recognized by financial economists. Investors rarely hold a single financial asset; instead they hold portfolios of financial assets. In this way, investors diversify risks and become less sensitive to price changes of individual assets. For example, total returns for an investor will be higher when low returns on an individual stock in a certain period are partly offset by higher returns from other stocks during the same period. Diversification is possible when stock returns are less than perfectly correlated. Modern Portfolio Theory (Markowitz 1952) addressed the question of which the potential set of portfolios investors should select. The main criteria in Modern Portfolio Theory (MPT) for selecting portfolios are their expected return and risk. The latter can be measured by the variance or standard deviation of the portfolio return. A portfolio with a relatively high variance or standard deviation is riskier, because the probability of yielding an unfavorable return is larger. According to portfolio theory, investors should first identify the efficient set of portfolios from all feasible portfolios. This means finding portfolios that have the highest possible expected return for a given risk or the lowest possible degree of risk for any given mean rate of return. Subsequently, investors can choose a portfolio among the efficient ones according to individual risk and return preferences (Elton and Gruber 1995).

The expected, or mean, return R_i of an individual asset A_i can be estimated by summing products of the actual return of that asset in a specific state of the economy and the probability that the corresponding state occurs. This can be represented by the following formula:

$$\overline{R_i} = \sum_{s=1}^{n} p_s R_s \quad (1)$$

where R_i is the expected return of an individual asset, p_s is the probability that state s occurs, and R_s is the actual return in that state s, with a total number of states equal to n.
The variance of the return of an individual asset is the average squared deviation of the actual return of that asset from its expected return. The variance V_i of an asset A_i can be defined as

$$V_i = \sum_{s=1}^{n} p_s (R_s - \overline{R_i})^2 \quad (2)$$

Another measure of dispersion is the standard deviation of an individual asset, SD_i, which can be calculated by taking the square root of the variance, thus $SD_i = \sqrt{V_i}$.

The expected return R^p of a portfolio can easily be obtained after calculating the expected returns of individual assets. Consider a portfolio consisting of individual assets $A_1, A_2, \ldots, A_n$ with corresponding shares in this portfolio $x_1, x_2, \ldots, x_n$, where obviously $0<x_i<1$ and the sum of all x_i equal one, since the shares are percentages. The expected return of such a portfolio can be estimated by adding the products of the expected return of the individual assets, R_i, and their shares in the portfolio x_i, which can be represented as

$$\overline{R^p} = \sum_{i=1}^{n} \overline{R_i} x_i \quad (3)$$

where the expected returns of individual assets, R_i, are defined by Eq. 1.

The covariance between individual assets in a portfolio has to be estimated in order to estimate the variance of a portfolio. The covariance between assets A_i and A_j corresponds to the expected value of the deviation of the actual return R_i of asset A_i from its expected return R_i times the expected value of the deviation of the actual return R_j of asset A_j from its expected return R_j. This can be represented by

$$\sigma_{ij} = E\{(R_i - \overline{R_i})(R_j - \overline{R_j})\} \quad (4)$$

Or equivalently by

$$\sigma_{ij} = \sum_{s=1}^{n} p_s (R_{is} - \overline{R_i})(R_{js} - \overline{R_j}) \quad (5)$$

where p_s corresponds to the probability that state s occurs, R_{is} to the actual return of asset A_i in that state and R_{js} to the actual return of asset A_j in that state, with a total number of states equal to n.

The covariance between two assets is positive when returns between assets are positively related and negative when returns between the assets are negatively related. The interpretation of the actual covariance figure is difficult. Therefore, it is suggested to calculate the correlation between two assets, which lies between -1 and 1. The correlation between two assets A_i and A_j is defined as

$$\rho_{ij} = \sigma_{ij} / (SD_i * SD_j) \quad (6)$$

where SD_i and SD_j are the standard deviations of the individual assets A_i and A_j.

The risk of a portfolio V^p can be represented by the variance of its returns, which can be estimated with the formula

$$V^p = \sum_{i=1}^{n} x_i^2 V_i + \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} x_i x_j \sigma_{ij} \tag{7}$$

where V_i represents the variance of the individual assets A_i, as can be estimated with Eq. 2 and σ_{ij} represents the covariance as can be estimated with Eq. 4. From Eq. 7 it follows that the portfolio variance is less than the weighted sum of the variances of the individual assets when the correlation between the assets is less than 1. In other words, diversification is possible as long as there is less than perfect positive correlation between the return of assets.

Portfolio diversification for a two asset case is illustrated in Fig. 1, which shows different sets of portfolios composed of two assets A and B for different correlations ρ between these two assets. The curved lines represent opportunity sets or feasible sets also called ‘efficient frontiers’; points on these curves can be obtained by selecting a mix between the two assets. Only one of these curves can exist in the real world: either ρ=1, or ρ=0.5 etc. The investor can only choose between different points on a curve having different risk and return characteristics for a given correlation between assets. Different portfolios can be developed by varying proportions of securities A and B in the portfolio. Points located more to the left represent portfolios with higher proportions of security asset A, which has a smaller expected return and risk than asset B. The straight line between the two assets represents possible return and risk characteristics of a portfolio composed of two assets (A and B) with a correlation of unity. The diversification effect applies to the curved lines, where the correlation is smaller than unity. The smaller the correlation between the two assets, the more bent is the curve indicating that higher returns can be earned for the same SD of the portfolio. Alternatively, the lower the correlation the lower the SD of a portfolio is for a constant expected return. The point MV, which is actually located on each of these curves, represents the minimum variance portfolio. This backward bending always occurs if ρ≤0, but may or may not occur if ρ>0. Obviously, no investor wants to hold a portfolio with an expected return below the minimum variance portfolio. Therefore, the efficient set lies between MV and B.

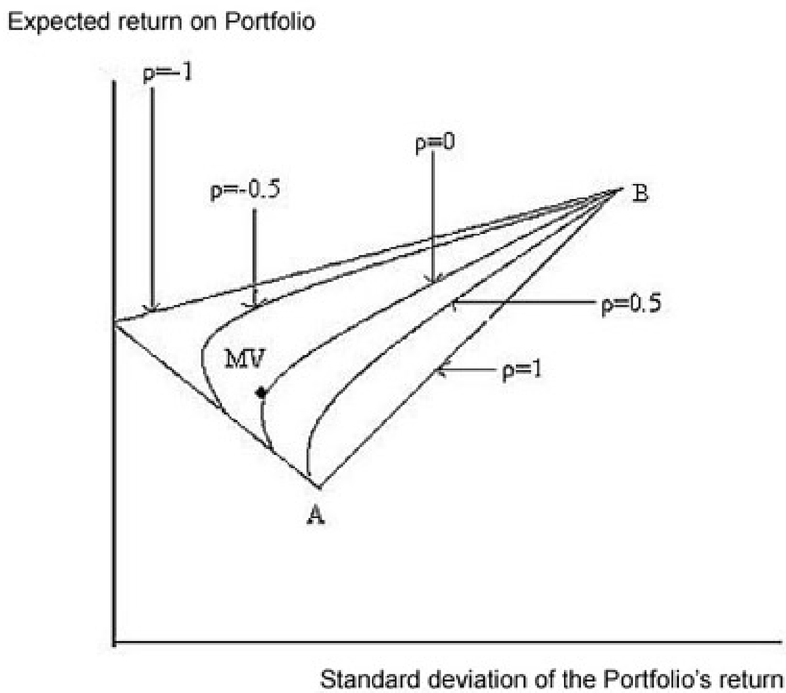
The above-described concept of MPT can provide additional value to current flood management practices. Most flood management investments have tended to focus on acceptable or tolerable risk defined as Probability * Damage with emphasis on the consequences of flooding more than probability. An MPT approach in flood management might add new information on the robustness of different investments, not only with respect to their return in terms of net costs and benefits, but also to the risk in achieving this return. This aspect is further explored in this paper.

CLIMATE CHANGE AND FLOOD MANAGEMENT IN THE NETHERLANDS

The Netherlands is one of the most densely populated countries in the world with 395 inhabitants/km². About half of the Netherlands, i.e., the western part, is below sea level, and millions of people live in these areas, which are protected by dikes. Also alongside the Rhine and Meuse Rivers there are areas lower than average river levels. The roots of this situation are historical. Many low-lying parts have been reclaimed from former lakes. Also subsidence of the soil induced by agricultural practice is one of the processes that causes increased exposure to floods to already low lying areas. This situation is further exacerbated by sea level rise.

The low-lying areas in the Netherlands are protected by a system of dikes and embankments along the main rivers and coastal areas. A so-called ‘dike-ring’ is a geographical unit bounded by its flood protection system of dikes (Fig. 2). It is also a separate administrative unit under the *Water Embankment Act* that was enforced in 1995. *The Water Embankment Act* aims to guarantee a certain level of protection against flooding for each dike-ring area. According to the *Act*, a dike-ring area should be protected against floods by a system of primary embankments, and each dike-ring has been designed such that it meets a safety norm. These safety norms are based on potential high flood levels with a certain probability. For example, a dike-ring with a safety norm of 1/10,000 means that this dike-

Fig. 1. The curved lines are "efficient frontiers" showing the most optimal risk-return values for different two assets portfolios against the variation in return. Each curve represents a different correlation ρ between the two assets. The minimum variation (point MV) represents an example of a minimum variance portfolio (Ross et al. 2002).



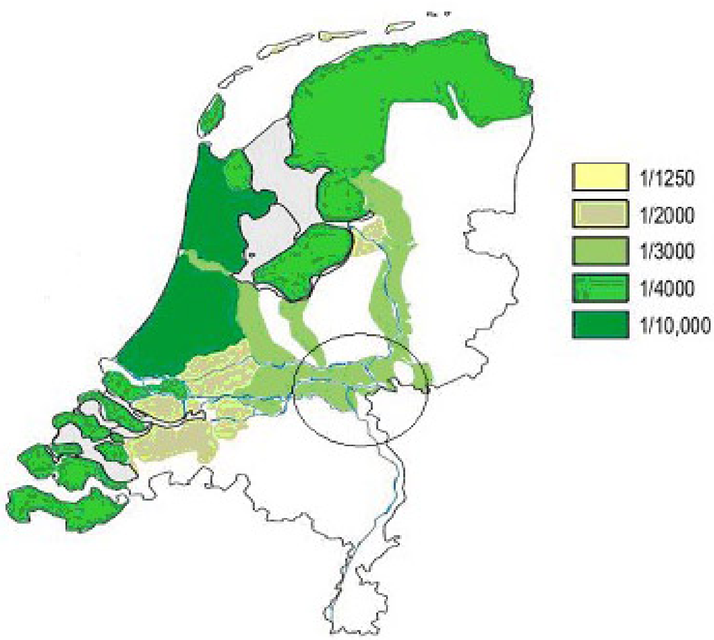
ring has been designed such that it can withstand a flood that occurs each 10,000 yr. These numbers have been derived from extrapolations based on historical data (Fig. 3). There are 95 dike-ring areas in total each having different safety norms. The most important safety norm areas are listed in Fig. 2.

Climate change and safety standards

Currently, safety standards in the Dutch part of the river Rhine are designed to withstand a flood that occurs once in 1250 yr (1/1250). The peak discharge, also called 'design discharge', for the Rhine at Lobith associated with an incidence of is estimated to be 16,000 m^3/s. Figure 3 shows the distribution of water discharges at Lobith and the corresponding incidence in years. The return time in years shown on the horizontal axis can be interpreted as a probability measure. The dots represent observed peak flows for the Rhine from 1901 to 2000 (Ten Brinke and Bannink 2004).

As the primary dikes along the River Rhine are currently designed for a maximum discharge of 15,000 m^3/s, additional measures in the area are currently needed as climate change may severely affect the hydrology of the river (IPCC 2001). New scientific results concerning climate change stimulated changes to the flood protection law, and additional measures are required now to protect the land from peak discharges of 16,000 m^3/s. For example, Aerts et al. (2006) estimate that peak flows of the lower Rhine may increase by about 5–8% by the year 2050. The upper and second highest lines represent climate change scenarios. The second highest line in Fig. 3 corresponds to an increase in peak flows caused by 1°C warming and the upper line corresponds to an increase in peak flows as a result of 2°C warming. The new probability of a design discharge of 16000 m^3/s and higher can be

Fig. 2. Map of the Netherlands showing the differentiation in safety norms. The location of the study area is indicated with the circle (DWW, 2005a,b).



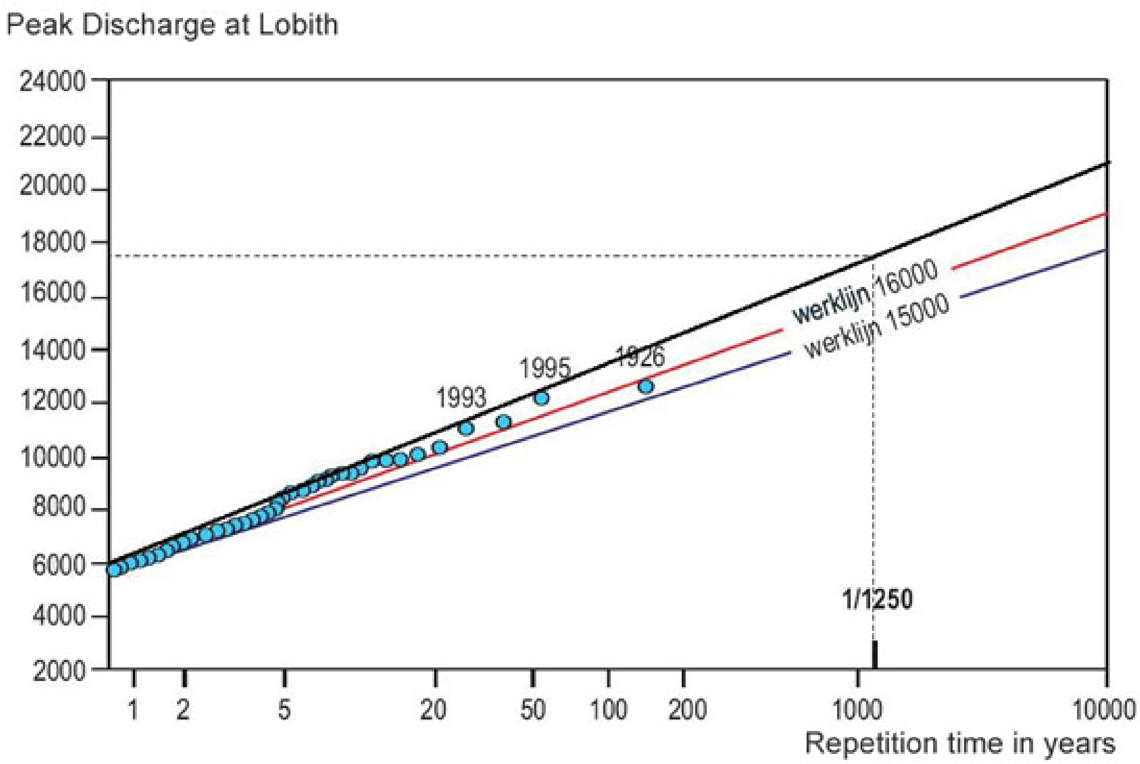
found by approximating the probability that corresponds to that discharge on the new, higher line. As is shown by the dotted lines in the Fig 3, the probability of having a 16,000 m^3/s and higher will increase to approximately 1/750 in 2050 with a temperature increase of 1°C and it will increase to approximately 1/550 when temperature increases by 2°C. Obviously, the probabilities of flooding due to dike failure will be lower when the government invests in protection measures.

APPLICATION OF MODERN PORTFOLIO THEORY TO FLOOD PROTECTION

We will now illustrate the principle of diversification by a numerical example using Modern Portfolio Theory (MPT) concerning four different flood management investments that are proposed for one representative dike-ring area ‘number 43’. The area is situated in the central part of the Netherlands (Fig. 4). The hypothesis is that investing in a portfolio of flood protection measures has the potential to increase expected return and lower risk compared to investing in individual strategies. Investing in primary dikes alone will result in a relatively high-expected return, i.e., prevented damage, but also in a large variance, i.e., risk, of this return. Combining dike investments with other investment strategies might lower the variance in returns, because these investments can prevent damage in situations of dike collapse, in which the return of the dike is actually zero. Therefore, damage extremes may be reduced when investments are diversified, i.e., lower investments in primary dikes but also investments in other damage reducing measures.

The aim of this application is to provide an illustration of the benefits of diversification of water management investments. The analysis is indicative in the sense that the returns of investment strategies are merely approximations. Note that we only focus on prevented economic property damage and damage to land use, including crop damage, within the dike-ring area. Macro economic costs and

Fig. 3. Peak discharges (m³/s) and their return time of the river Rhine in the Netherlands at gauging station Lobith. Werklijn 15,000 and 16,000 stand for the design discharges 15,000 and 16,000 m³/s respectively that occur 1/1250 yr under different extrapolations. The upper and second highest lines represent design discharges under two different climate change scenarios (Botzen and van den Bergh 2006).



casualties are not considered in this analysis. The maximum potential damage is estimated at 17,993×10⁶ Euro (DWW 2005*b*).

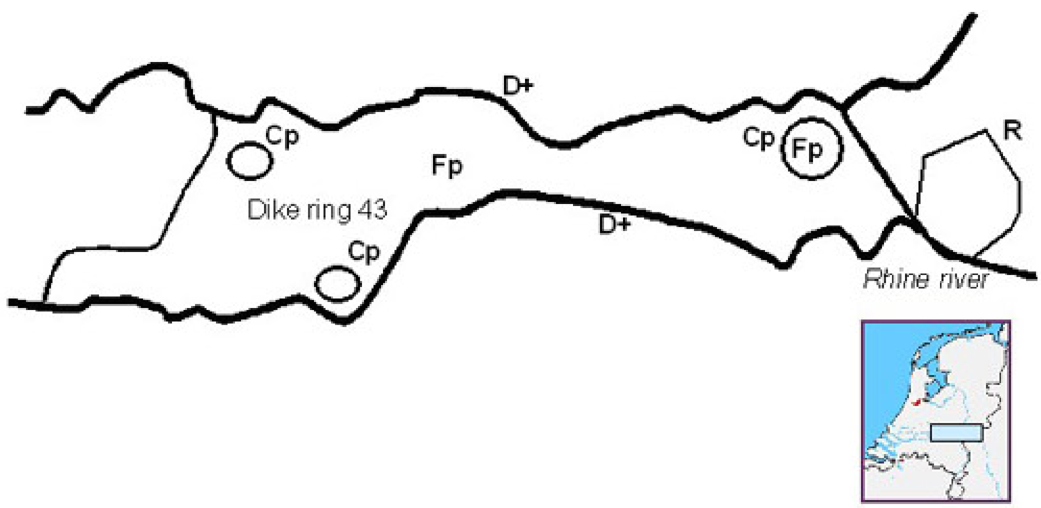
In this application, four states are defined each representing different levels of river discharges of the Rhine at Lobith, i.e., the location where the Rhine enters the Netherlands. The probabilities of observing these discharges are likely to change as a result of climate change. Therefore, one base line scenario and two climate change scenarios are defined, which generate different probability distributions for each of the four states. Finally, four assets will be considered, which are investment strategies that prevent flood damage. The probabilities are listed in Table 1.

The discussion below carefully defines the states of peak discharges, climate scenarios and assets that are used in the application.

States

Four states of nature are defined, which correspond to different peak discharges of the river Rhine. One state (‘State D’) is a situation where no damage will be caused (all discharges below 16,000 m^3/s), because current dike designs are sufficient to withstand these discharges. The other three states (A, B and C) concern other intervals of peak discharges that will cause damage above the current safety level of 16,000 m^3/s. For these flood states we have selected three intervals of discharges: C: 16,000–17,000, B: 17,000–18,000 and A: >18,000

Fig. 4. Schematic overview of the possible flood protection investments in dike-ring area 43 in the central part of the Netherlands. The four possible investments are: Asset D+, main dike reinforcement; Asset Cp, compartments around urban areas; Asset Fp, flood protection residences; Asset R, Upstream retention area.



m^3/s (Table 1). The probabilities for each possible state under each climate scenario can be derived from the lines presented in Fig. 3 starting with the probability of state A (>18,000 m^3/s). The probability of state A (>18,000) is directly calculated from Fig. 3 by one divided by the repetition time corresponding to 18,000 that is shown on the horizontal axes. The probabilities of the intervals C and D are obtained by subtracting the probability of observing the maximum discharge and higher in the interval from the probability of observing the minimum discharge and higher in the interval. For example, the probability of the occurrence of a discharge between 17000 and 18000 (state B) is calculated by subtracting the probability of observing a discharge of 18,000 and higher from the probability of observing a discharge of 17,000 and higher. The probability of having state D (discharges <16,000 m^3/s) is calculated as 1 minus the probabilities of states A+B+C, in order to make the probabilities add up to unity. The probability of state D can be interpreted as the probability that no flood damage occurs in a given year.

Climate scenarios

Table 1 shows how the probabilities of observing a particular state change under a different climate scenario. We have calculated the probabilities for each state A, B, C and D according to three climate scenarios: current climate, climate change 1 (CC1) and climate change 2 (CC2). The probabilities of observing a particular state under the CC2 scenario can be derived from the upper line in Fig. 3 and the probabilities under the CC1 and current climate scenarios can be derived from the second-highest and third-highest lines respectively. The probabilities for each state under a specific climate scenario should add up to ‘1’. The purpose of these climate scenarios is to examine how portfolio returns and variances change when flood probabilities rise as a result of climate change.

The assets

Flood protection measures

In and around the case study area, four different flood protection investments will be considered to cope with an increase in future peak discharges.

Table 1. Probabilities of the different states, i.e., possible discharges, under three different climate scenarios, e.g., current, climate change low, and climate change high. For each investment, the returns, expressed as prevented damage loss, are showed for each possible states A, B, C, and D (from DWW 2005*a*, 2005*b*).

	States			
	A	B	C	D
Discharge[m³/s]	> 18000	17,000–18,000	16,000–17,000	< 16000
Climate scenarios	Probability			
Current	0.000125	0.000250	0.000800	0.998825
Climate Change low scenario (CC1)	0.000167	0.000667	0.001333	0.997833
Climate Change high scenario (CC2)	0.000667	0.001333	0.001818	0.996182
Assets	Actual Returns [10^6 Euro]			
D+: Higher dike ring	0	0	17993	0
Cp: Compartments	0	8000	12000	0
Fp: Flood proofing houses	3000	3000	3000	0
R: Retention areas	-4000	14000	14000	0

These measures are targeted towards lowering water levels under peak discharges thereby reducing the risk of dike failures, increasing protection by building dikes or limiting economic damage once a flood occurs. The four investment measures can be characterized by their actual returns under different states (Table 1). The protection measures that are being considered are shown in Fig. 4, and are briefly discussed below. Note that we do not take investment costs into account but only focus on returns measured as the ‘prevented damage loss’.

Asset D: Enforcement dikes

Enforcement of the primary dikes of the dike-ring area. This refers to heightening the dikes at the design discharge level of 17,000 m^3/s. This means that after having invested in this option no damage can be expected at discharges from 17,000 m^3/s or lower. At higher discharges, the damage will be equal to the maximum potential damage, which is estimated at 17,993 million euro. The damage prevented in state C (or expected return) equals the maximum potential damage.

Asset Cp: Dividing a dike-ring into compartments

Compartments. This refers to leaving the current primary dikes at the safety level below the design discharge of 16,000 m^3/s, but developing new ‘internal dikes’ within the dike-ring for protecting the most economic valuable areas, such as urban areas and horticulture areas. In this example we assume three extra dikes: two that protect urban areas and one that protects horticulture areas. The new 2 internal dikes for urban areas can withstand floods in the state B: 17,000-18,000 m^3/s. The new internal dike for horticulture areas can withstand floods in the state C: 16,000-17,000 m^3/s. The potential damages for urban areas and horticulture areas are estimated at 8,000 million euro and 4,000 million euro respectively (DWW, 2000b). Hence, this result in 12,000 million euro avoided damage for *Asset Cp* under State C and 8,000 euro avoided damage under State B.

Increasing resilience to flooding of individual properties

Flood proofing of residences. This refers to developing additional flood protection measures for individual houses including the development of floating houses, heightening houses, etc. These measures limit economic damage once a flood occurs. It is estimated that through additional flood protection measures for all houses in the area, about 3,000 million euro damage can be prevented in case of any of the three flood states from 16,000 m^3/s and more that are considered.

Asset R: Creating upstream retention areas

Retention areas. This refers to the development of upstream areas that are designed to temporarily store water in case of a peak discharge. In case of a peak discharge, the area will be deliberately flooded to cut off the peak thereby lowering the water levels downstream. In this example, it is expected that using a 'flood storage area' will prevent damage to dike-ring area 43 at discharge levels between 16,000 and 18,000 m^3/s. However, although the retention area only holds a few urban settlements, which can be quickly evacuated in case of a flood, flooding the retention area will cause economic damage to that area (crop damage, nature area's, etc) of about 4,000 million euro.

Calculation of portfolio return and variance

By inserting the above-described information in Eqs 1 to 7 it is possible to calculate sets of flood protection portfolios. For this purpose, firstly the expected returns and variances of the returns per individual assets have to be calculated. Subsequently, expected returns and variances of portfolios can be estimated. The expected return R_i for each individual asset (Eq. 1) can be calculated using the actual returns and probabilities that are provided in Table 1. For example, the expected return for Asset D+ under the current climate scenario is calculated as follows:

$$\overline{R_{D+}} = 0.00013*0 + 0.00025*0 + 0.0008 *17993 + 0.99883*0 = 14.3944 \qquad (8)$$

The variance V_i for each individual asset can be calculated using Eq. 2 yielding the numbers as shown in Table 2.

The estimated expected returns and variances shown in the table indicate that the expected return of investment strategy D+ is highest, but the variation in returns is also highest for this investment. This means that the prevented damage on average is high when the government decides to invest in heightening primary dikes. The disadvantage of this strategy is that risk, defined as variance, is very high as well since the dike only prevents damage up to some level of river discharge and for higher levels of discharge the full potential damage is suffered. The other investments strategies have lower expected returns, but the variance in these returns is also lower. Expected returns are lower because these investment strategies do not prevent all of the maximum potential damage in a state. The advantage of these investment strategies is that risks are smaller, since they prevent damage in more than one state. The individual risk and return characteristics of these assets suggest that a combination of these investments might be desirable in order to reduce overall risk. This will be shown by calculating expected returns and risks of different portfolios of assets.

The expected portfolio return can be calculated using both the expected returns of the individual assets as displayed in Table 2 and the shares x_i of each asset A_i in a portfolio. By choosing a variety of shares, different portfolios can be constructed. These shares can be interpreted as the percentage share of total government budget available for water management investments that is spent on a specific investment strategy. Obviously, expected returns of investments depend on investment shares. For the case of simplicity, it is here assumed that by lowering the investment share in heightening primary dikes, the resulting primary dike will be lower. The prevented damage of the D+ investment strategy will be lower as well. Lowering the investment share in asset Cp implies that the area protected by compartments will be smaller and the damage prevented by these compartments will be lower as well. Decreasing the investment share of flood proofing houses means that fewer houses will

Table 2. Expected return, variance, and standard deviation (SD) per asset under the current climate scenario.

	Expected return [10^6 Euro/y]	Variance	SD	SD / Return
Asset D+	14.39	258791.24	508.72	35.34
Asset Cp	11.60	131065.44	362.03	31.21
Asset Fp	3.53	10562.57	102.77	29.16
Asset R	14.20	207598.36	455.63	32.09

be flood proofed and correspondingly, damage prevented by this strategy will be lower compared to the 100% flood proofing case. Investing less in retention areas implies that the areas that are deliberately flooded are smaller, which again lowers the damage prevented in dike-ring area 43. Evidently, this reasoning is reversed when investment shares of specific investments are increased.

By filling in expected and actual returns per asset using Eq. 4 and calculating the portfolio variance using Eq. 7, the expected returns and variances of portfolios can be estimated. These results for several portfolios are presented in Figs 5 and 6. Figure 5 shows two asset portfolios and Fig. 6 shows two, three and four asset portfolios under the current climate scenario – hence using the probabilities for each state under the current climate scenario as displayed in Table 1. Finally, as a sensitivity analysis, the same calculations can be conducted using the probabilities of the two remaining climate scenarios CC1 and CC2 (Table 1). The results of these calculations for portfolios consisting of all four assets are displayed in Fig. 7. These results will be discussed in detail in the next section.

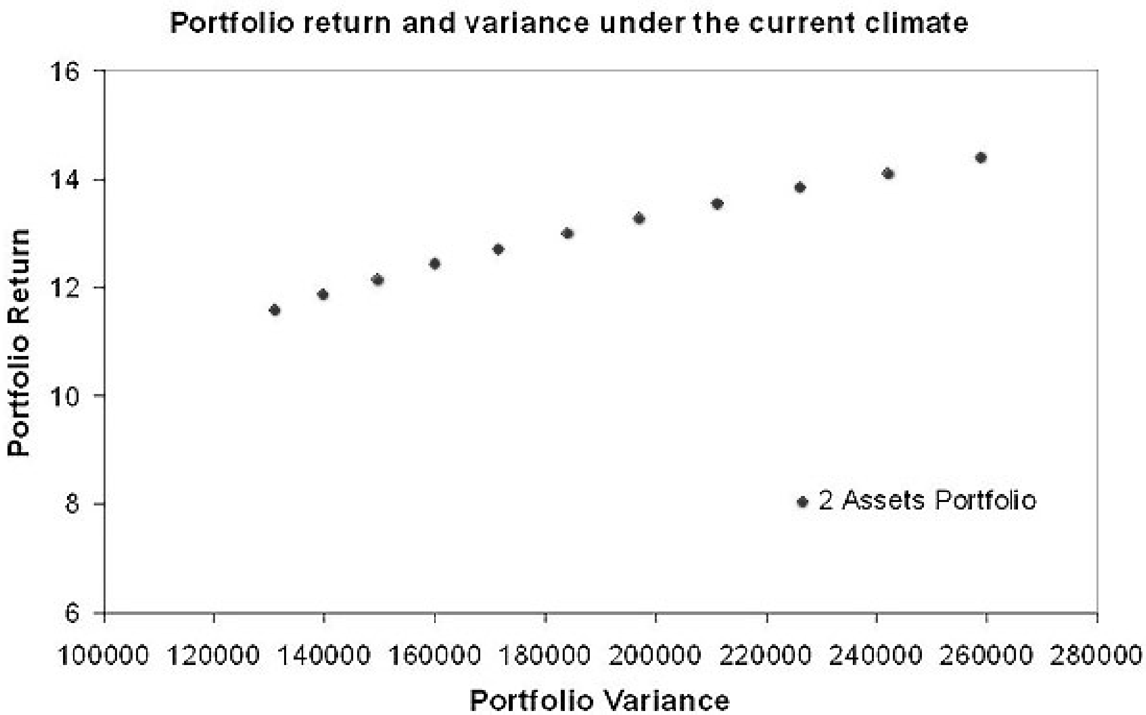
DISCUSSION

Interpretation of results

Figure 5 shows the portfolio variance and expected return for several portfolios that consist of the assets D+ (heightening dikes) and Cp (compartments). The upper point represents the portfolio with a 100% share in D+ and 0% in Cp, which corresponds to a high expected return but also a high risk. Portfolios that are positioned more to the left can be obtained by increasing the investment share in Cp and reducing the share of D+. The middle point is the portfolio that consists of 50% of D+ and 50% of Cp, and the lower left point represents the 100% Cp portfolio. This figure shows that increasing the investment share in Cp reduces overall risk. However, this is only possible at the expense of sacrificed expected return. This analysis shows that diversification of investments has the potential to reduce overall risks, compared to the 100% D+ portfolio, or increase the expected return, compared to the 100% Cp portfolio. Thus, water managers can obtain their desired risk and return by varying investment shares.

Benefits of diversification can be larger when more investments are available, as is apparent from Fig. 6. This figure adds a three-assets portfolio curve, which consists of the assets D+, Cp, and Fp (flood proofing), and a four-assets portfolio curve consisting of assets D+, Cp, Fp and R (retention areas). From this figure it is apparent that adding assets to the portfolio increases the range of possible return and risk characteristics available. The overall portfolio risk can be reduced considerably when the portfolio includes asset Fp, since the three-assets portfolio curve includes variances between 38,000 and 130,000, which cannot be attained by the two-assets portfolio curve. Table 3 explains why adding asset Fp to the two-asset portfolio considerably lowers the portfolio variance; it appears that the correlation between the Assets Fp and D+ is relatively low at 0.82 (Eq. 6). The lower the correlation of returns between investments the

Fig. 5. Portfolio return and variance values for portfolios consisting of two assets (D+ and Cp) under the current climate scenario.



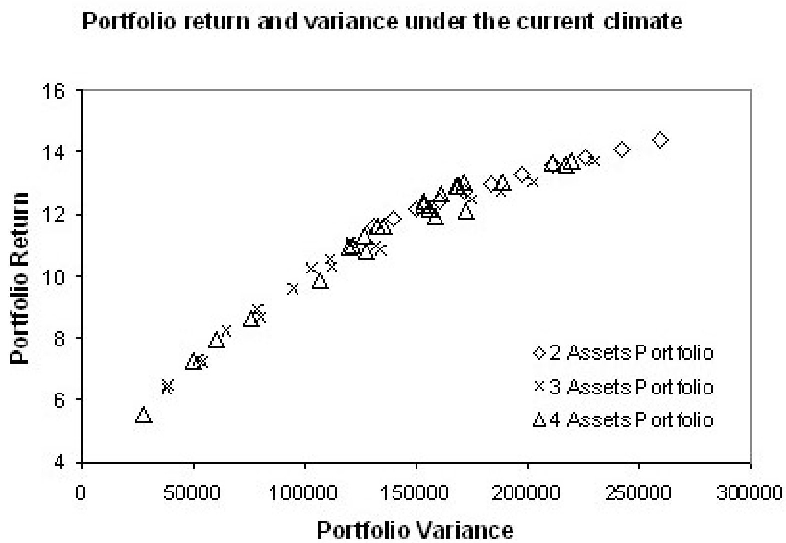
larger are the benefits of diversification, as has been discussed in Section 2.

The portfolio variance can be decreased slightly relative to the three-assets portfolio when the fourth asset, R, is included in the portfolio. The lowest variance portfolio is achieved by having approximately 60–70% of asset Fp, around 10–20% of assets D+ and Cp, and a small fraction (5–10%) of asset R in the portfolio. Apparently, asset Fp correlates less well with the other assets in terms of their return and hence diversifies the portfolio variance relatively well. Furthermore, the four-assets portfolio curve has a slightly higher expected return than the two- and three-asset portfolios for variances between 150,000 and 170,000, whereas expected returns are larger for the three-assets portfolios around variances of 100,000. This suggests that different portfolio mixes are desirable for different risk preferences.

Furthermore, when studying Fig. 7, it is clearly shown that climate change will have an important impact on the portfolio returns and variances. This figure shows the expected return and variance of several portfolios that consist of all four assets under the three aforementioned climate scenarios. As the probability of flooding will increase under both climate change scenarios CC1 and CC2, the expected portfolio return (‘the prevented damage’) will go up as well, as for most assets the individual expected returns increase. Obviously, investing in preventing and limiting flood damage has a higher return when the probability of damage increases. Note, however, that the portfolio variance increases as well under both climate change scenarios CC1 and CC2. This suggests that the necessity of diversification of water management investments increases due to climate change, in case an increase in risk is regarded as undesirable. For example, the individual risk level of the D+ strategy (100%D+) in the current climate scenario can only be obtained through diversification in the CC1 scenario.

This application indicates that diversification of water management strategies has the potential to

Fig. 6. Portfolio return and variance values for two (D+ and Cp) , three (D+, Cp and Fp) and all four assets portfolios under the current climate scenario.

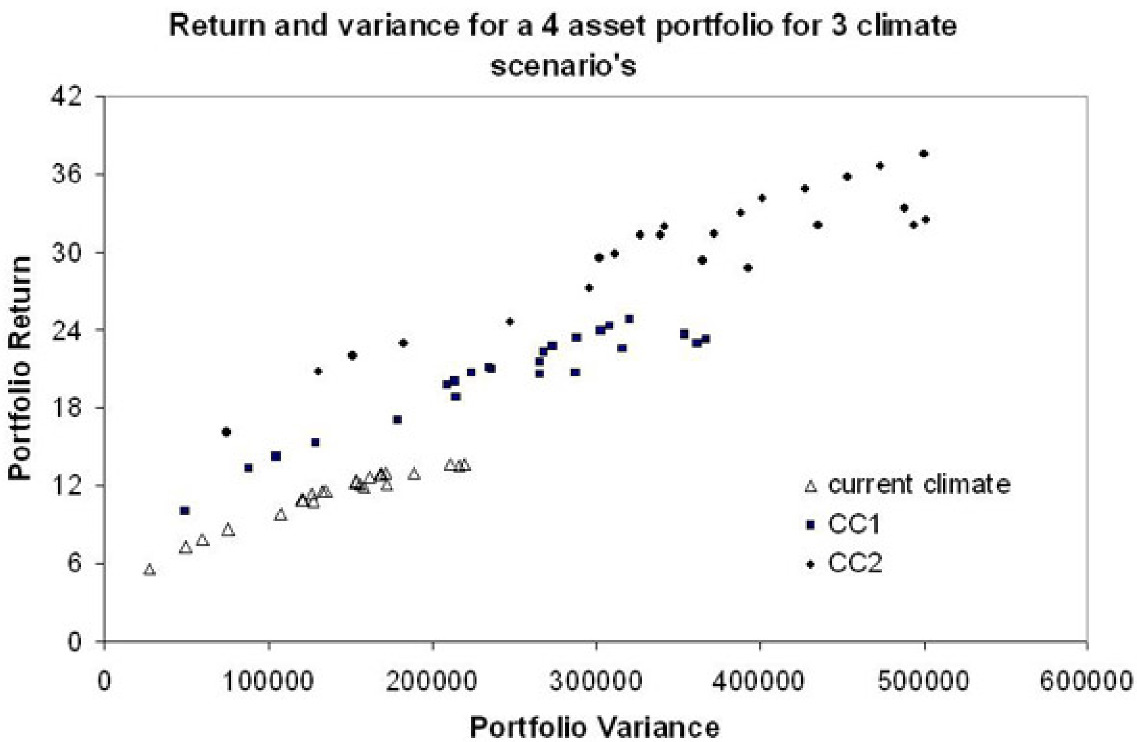


increase expected returns or reduce risks. The variance of expected returns can be reduced considerably compared to the strategy of investing in heightening of primary dikes only. Therefore, the probability of suffering extreme flood losses reduces when investments in primary dikes are combined with the other investments discussed in this paper. The analysis indicates that in most cases a trade-off between risk and return exists, which implies that lower risk levels can only be obtained by accepting lower expected returns. Calculations of risks and returns of portfolios under different climate scenarios show that increases in risk, i.e., variance in returns, can be limited through diversification. The costs of these investments, should then be subject to an evaluation as well, but this is not the topic in this paper. It should be noted however that real-world trade-offs between investments within a portfolio can only be realized if proportional investment is meaningful in practice. For example, it is not realistic to develop a retention area for only 30%. Without the remaining 70% of the investments it simply will not function. In this case, the 30% would then mean that a smaller retention area will be developed which stores less water than the case in which 100% would be invested in upstream retention. Hence, a proper definition of what a proportion of an investment means in practice is very important.

Modern Portfolio Theory and cost-benefit analysis

Cost benefit analysis (CBA) plays a major role in Dutch flood management for deciding where and how to invest in new flood defence systems. Research in cost benefit analyses for flood management tend to focus more on the differentiation between direct and indirect economic damage in order to assess economic vulnerability to floods (van der Veen and Logtmeijer 2005). Hence, most CBA studies applied to flood risk management consider options and or combinations of interventions. Most studies also consider a range of multi-criteria in the evaluation. However, variance is not always explicitly considered in most studies and in some cases considering variance would provide a broader understating of the effectiveness of interventions

Fig. 7. Portfolio return and variance values for portfolios consisting of four assets under the current, CC1 and CC2 climate scenarios.



and hence would further help evaluating different investment options.

In cost-benefit analysis there is a growing attention for the role of uncertainty in the decision-making process (Boardman et al. 2006). Basically, expected value over the contingencies, the public policy alternatives, was seen in the past literature as the important item to be assessed. This expected value leads to an ex post measurement of expected social surplus, incorporating changes in consumer surplus, producer surplus and net income for governments. Applying portfolio theory in cost-benefit analysis for flood management would involve the straightforward computation of expected social surplus over the sets of flood management alternatives. Examples of such applications can be found in health economics (O'Brien and Sculpher 2000, Sendi et al. 2004, Sendi and Rutten 2004, Sendi and Zimmermann 2004).

CONCLUSIONS

Long-term developments such as climate change are inherently uncertain and hence it is difficult to predict what implications it has for current investments in flood protection in the Netherlands. The paper presented a numerical example of how to develop portfolios of flood management activities that generates the highest return under an acceptable risk for an area in the central part of the Netherlands. Although the example is relatively simple, with many assumptions, it can be stated that Modern Portfolio Theory (MPT) encourages a systematic discussing of the relationship between the return and risk of individual activities and the return and risk of complete portfolios. It also showed how important it is to understand the correlation of the returns of various flood management activities and that adding partly uncorrelated assets lowers the risk of the total portfolio. As such MPT is a valuable tool to learn and re-evaluate portfolios once more

Table 3. Correlation coefficients between pairs of assets using Eq. 6.

Pair of Assets	Correlation
Asset D+ / Cp	0.94
Asset D+ / Fp	0.82
Asset D+ / R	0.93
Asset Cp / Fp	0.93
Asset Cp / R	0.99
Asset Fp / R	0.89

information about flooding and their probabilities becomes available.

Apart from portfolio return and variance, the choice for a particular flood protection portfolio depends obviously on more factors than those mentioned in the case study example. For example, the investment costs of the different assets are neglected. Another restriction is the budget available for new investments in flood protection and it might appear that through budget limitations, a less preferred portfolio will be selected. Furthermore, the perceptions of stakeholders in the Netherlands, e.g., civilians, government, waterboards, etc., concerning living with uncertainties with respect to floods are still very much targeted at full protection; hence, aiming at the highest returns. This means in practice that strengthening dikes is still the most preferred option.

The method presented in this paper clearly has limits and we propose the following issues that can be included in future research:

1. One aspect for further research is to consider multiple goals. In this study, we only consider the return values related to potential damage. However, in practice, social and environmental aspects also play an important role in investment decisions. We therefore propose to combine aspects of this research with aspects of operational research, especially optimization, in order to apply MPT to multiple conflicting returns in which not only potential damage is minimized but also environmental values are maximized (e.g. Penning-Rowsell et al. 2005). Within this context, available budget could be a boundary condition under which optimal portfolios are evaluated.

2. MPT might also be a valuable quantitative indicator for the development of adaptive water management regimes. Within this context, MPT might add information on the type of investments stakeholders may develop and addresses such questions as: what kind of measures or policies are important for including in new water management portfolios, who is currently responsible for developing each individual measure and how should this be changed, and what are the sources of future uncertainty? Research on adaptive water management could integrate quantitative insight from MPT analysis within assessing the adaptiveness of water management systems and institutions.

3. Further research into climate vulnerability should investigate whether the risk-return ratio might be an indicator that allows water and climate researchers identifying the vulnerability of the water system and related proposed investments in this system.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol13/iss1/art41/responses/

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